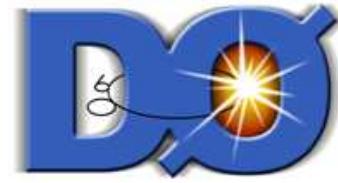

Top Quark Mass Measurements at the Tevatron

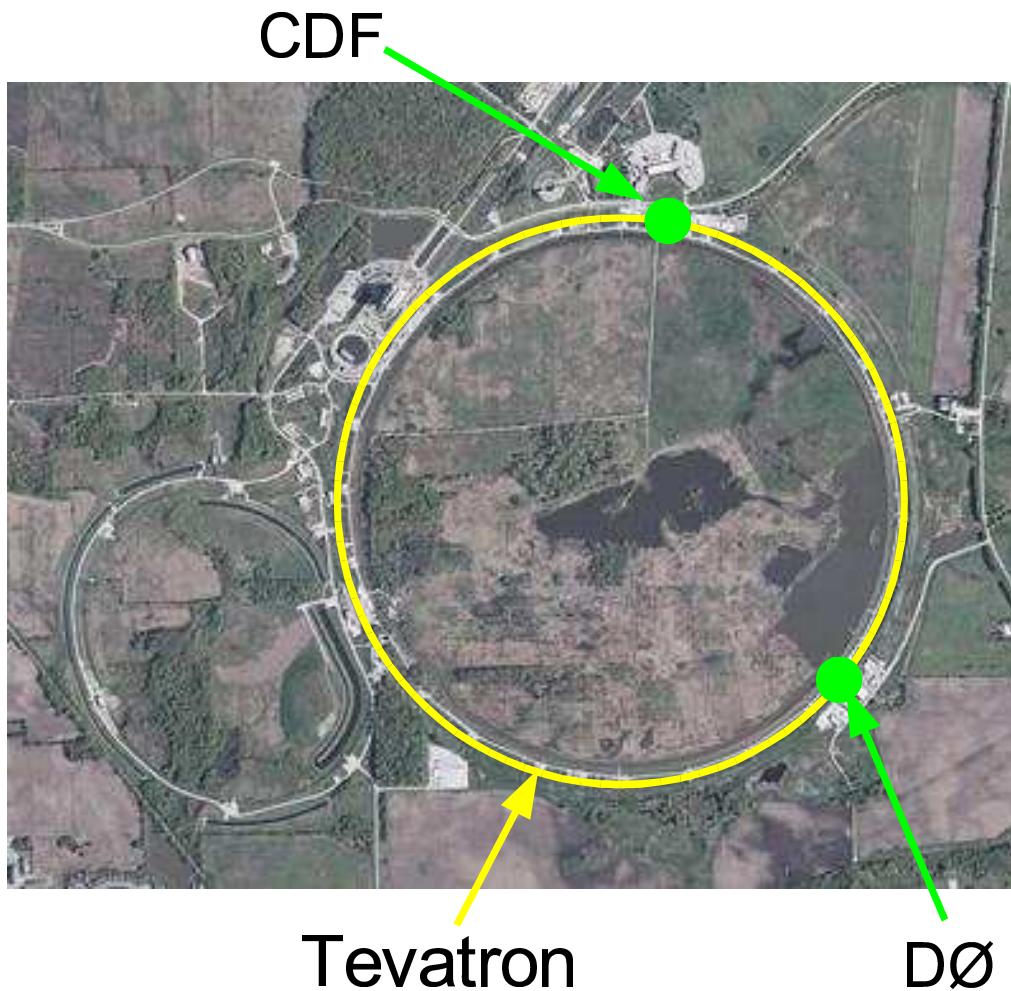
- Introduction
 - Tevatron, CDF, DØ
 - Top quark mass
- Mass Measurements in Run II
 - Dilepton
 - Lepton plus jets
 - Systematics
- Summary

Alan Magerkurth
University of Michigan

On behalf of the CDF
and DØ collaborations

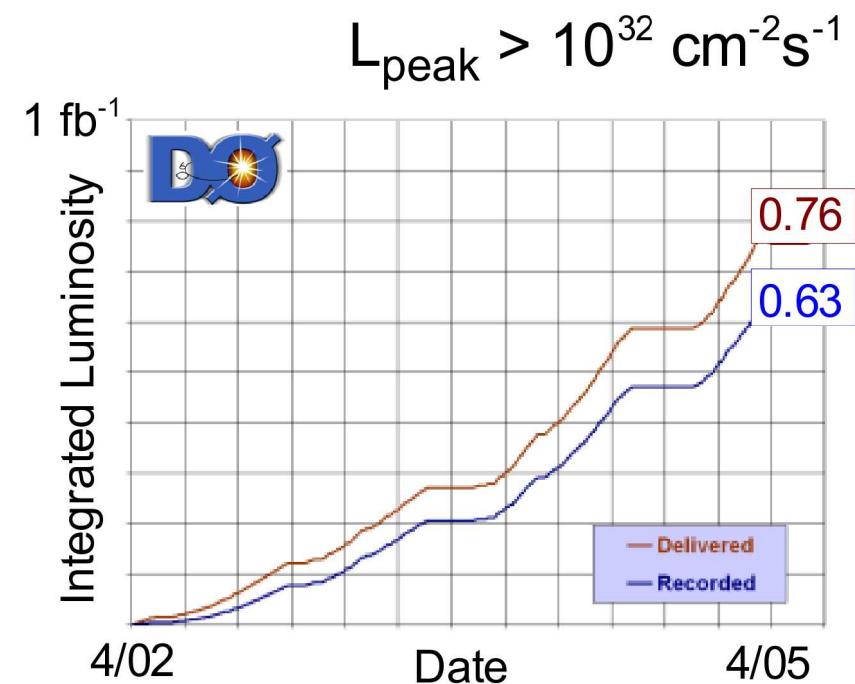


The Tevatron Run II



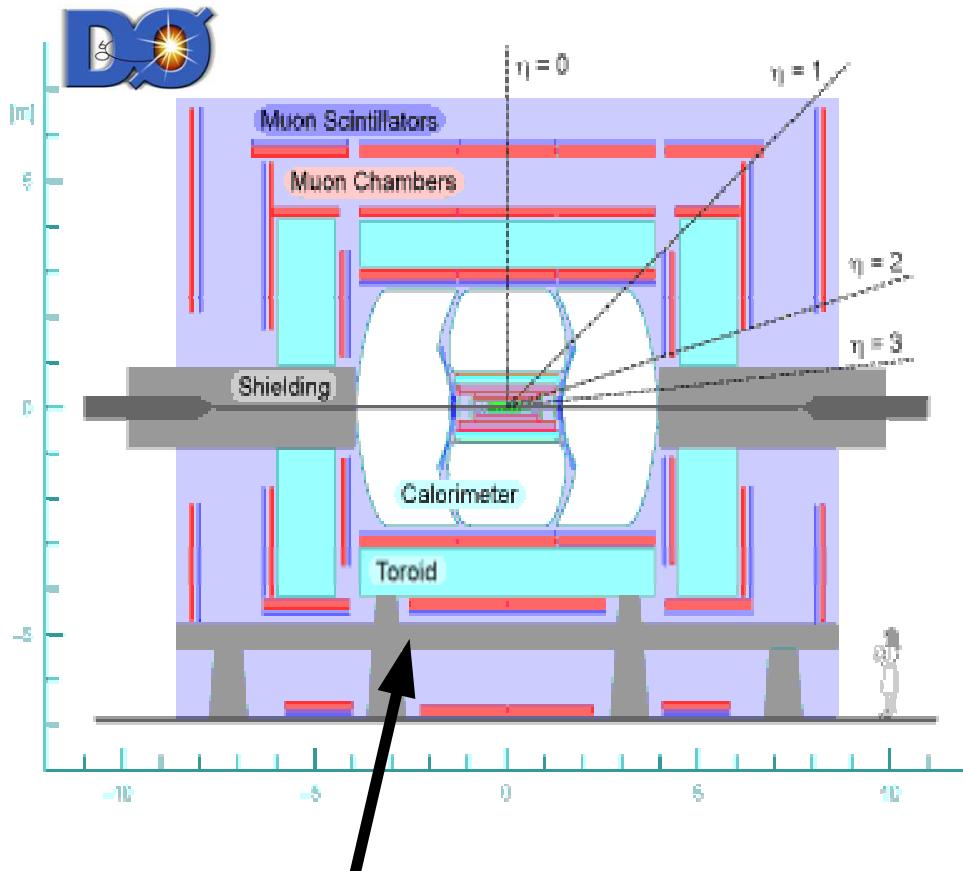
Both experiments have recorded over 600 pb^{-1}

Analyses presented here use $\sim 150\text{-}320 \text{ pb}^{-1}$



World's only top factory

CDF and DØ Detectors

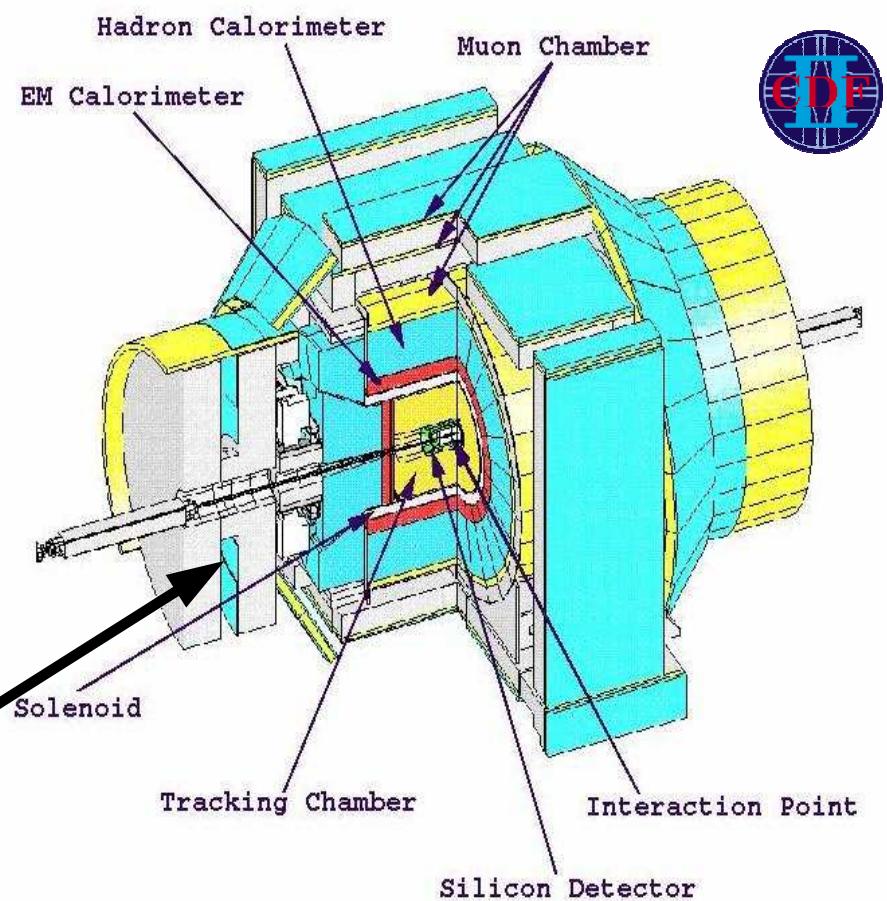


Excellent coverage
New preshower detectors

Excellent tracking resolution
New forward calorimeter

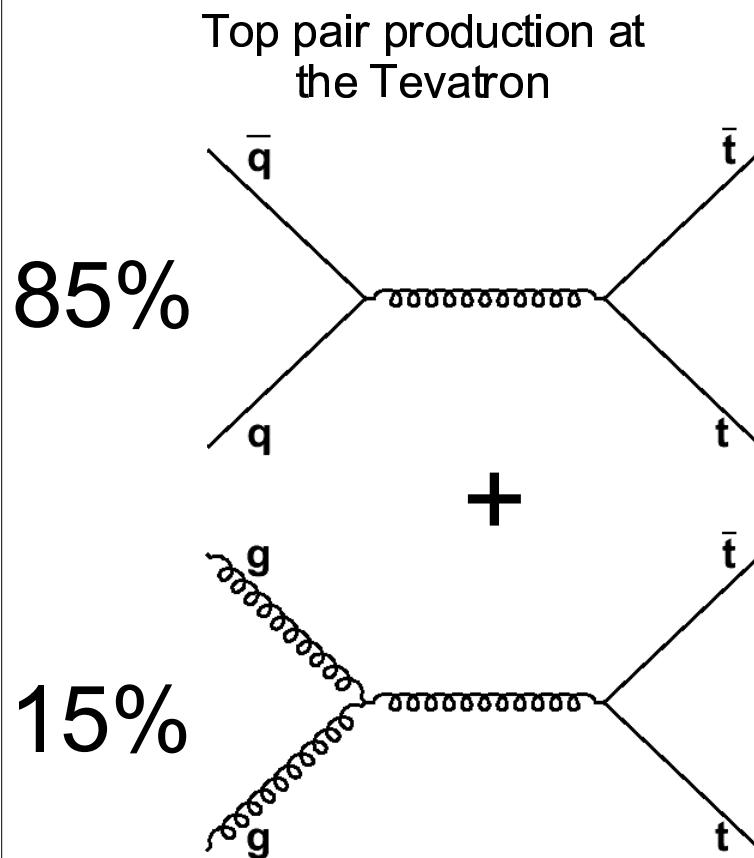
Both experiments:

- New tracking systems
- Upgraded electronics, trigger, DAQ



Top quark production and decay

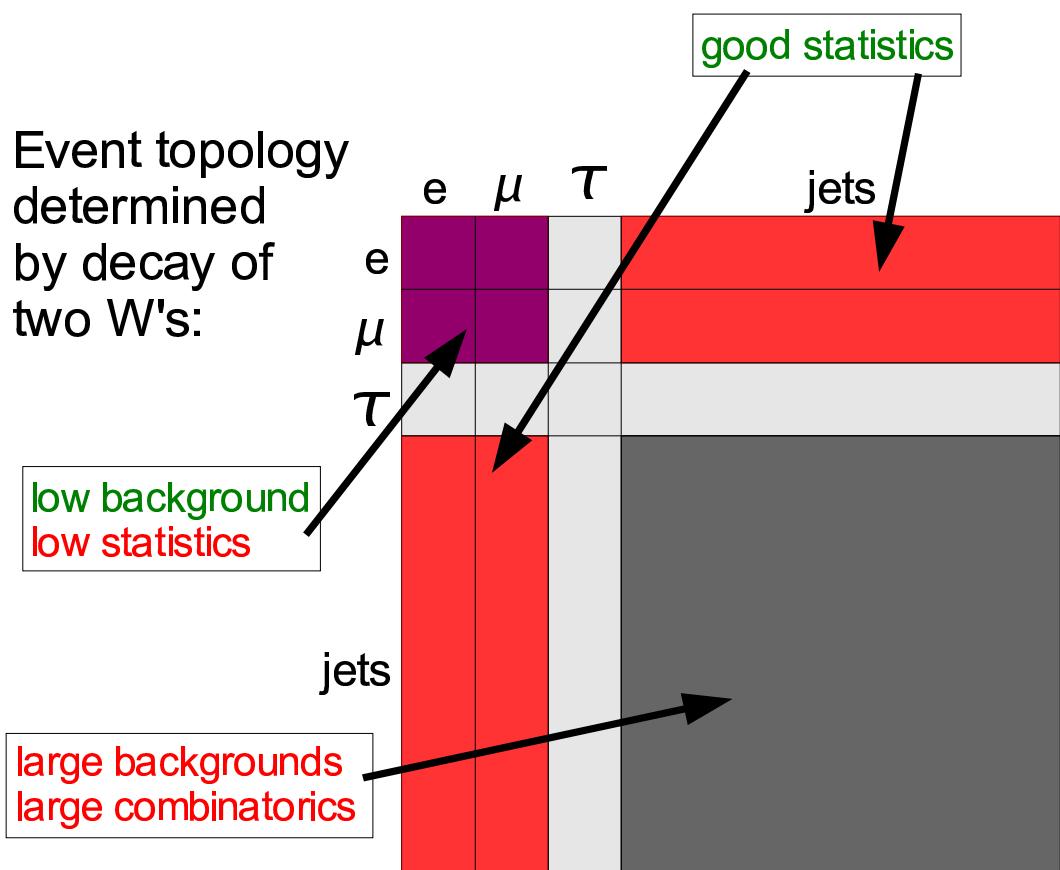
Top quark mass measured
in $t\bar{t}$ events



Top quark is unique among fermions:
 $M_t > M_W \rightarrow t \rightarrow W b$

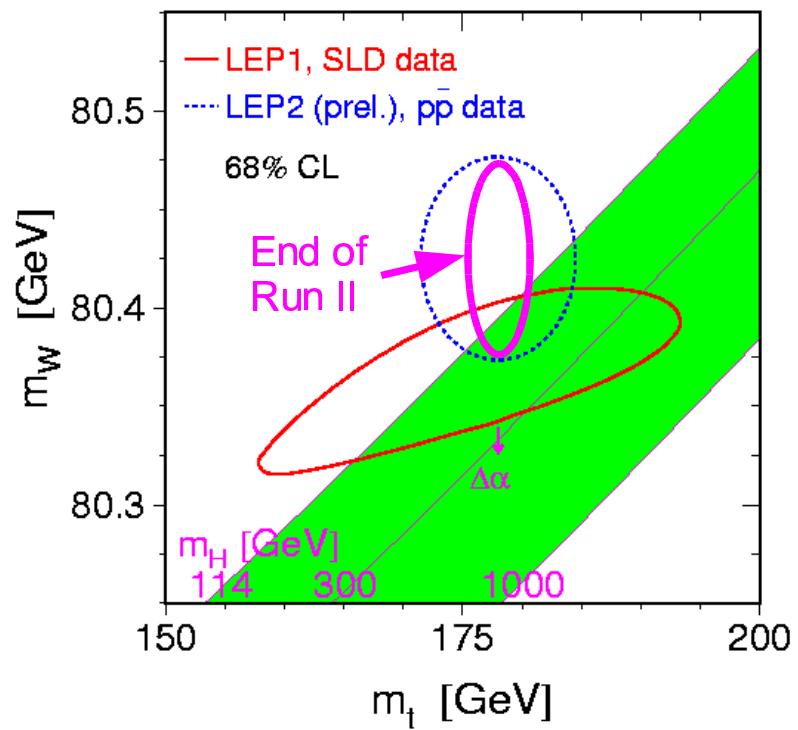
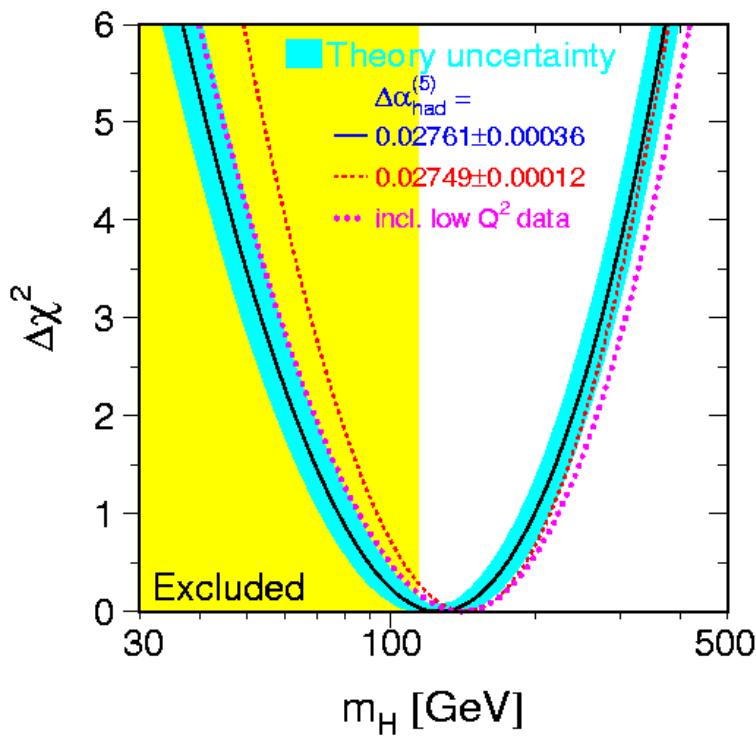
$$\begin{aligned} BR(W \rightarrow \text{leptons}) &= 1/3 \\ BR(W \rightarrow \text{quarks}) &= 2/3 \end{aligned}$$

Event topology determined by decay of two W's:



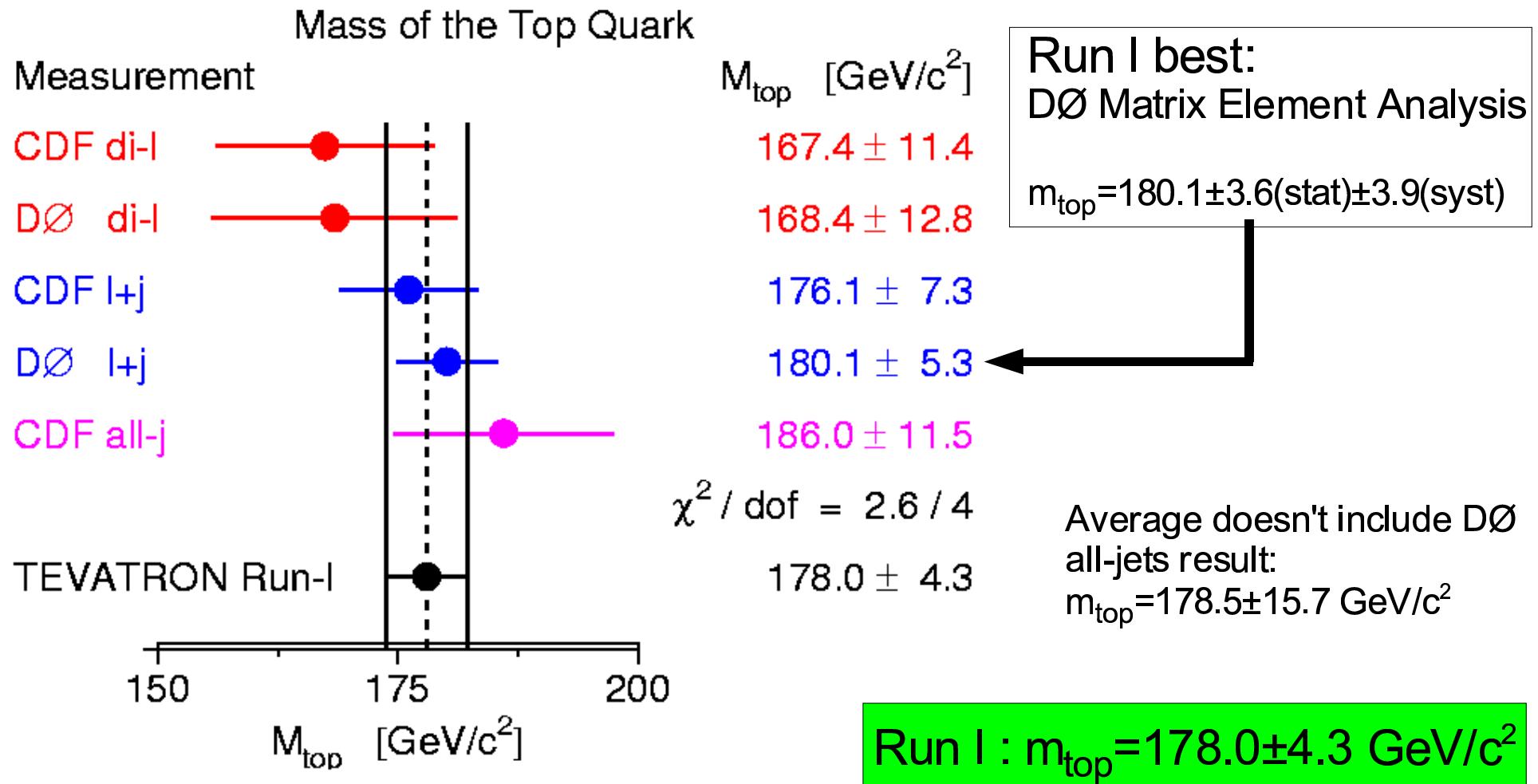
Why top quark mass?

- Fundamental parameter of the Standard Model
- Constraint on Higgs mass
- Competition for best-known quark mass ($m_b \sim 2.5\%$)



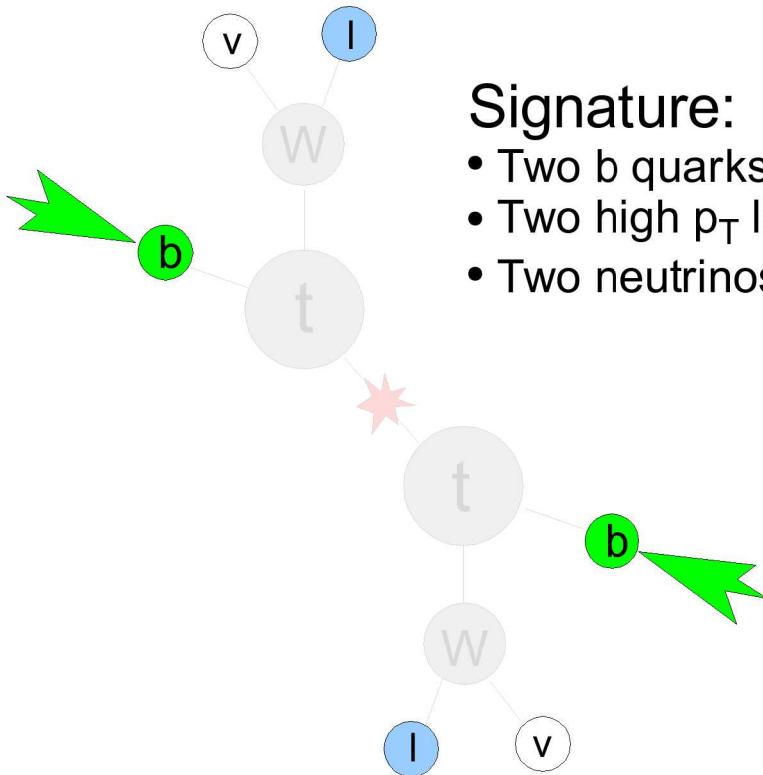
Status of top quark mass measurement

CDF and DØ Run I Results ($100-125 \text{ pb}^{-1}$):



Top Quark Mass Measurements in Run II

Dilepton Channel



Signature:

- Two b quarks
- Two high p_T leptons
- Two neutrinos

Typical Event Selection:

- One high p_T lepton (>15 GeV)
- Oppositely charged high p_T lepton or isolated track (>15 GeV)
- Two or more high p_T jets (>20 GeV)
- Missing E_T (>25 GeV)

Backgrounds:

- Diboson (WW, WZ, ZZ)
- Drell-Yan
- $Z \rightarrow \tau\tau$
- W+jets with fake lepton

Small branching ratio → low statistics

Large S/B

Two neutrinos → underconstrained kinematics
Need to assume knowledge of some quantity

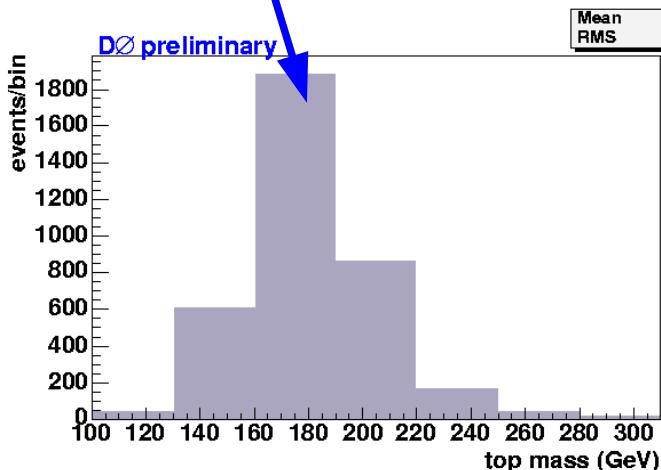
Matrix Weighting Method



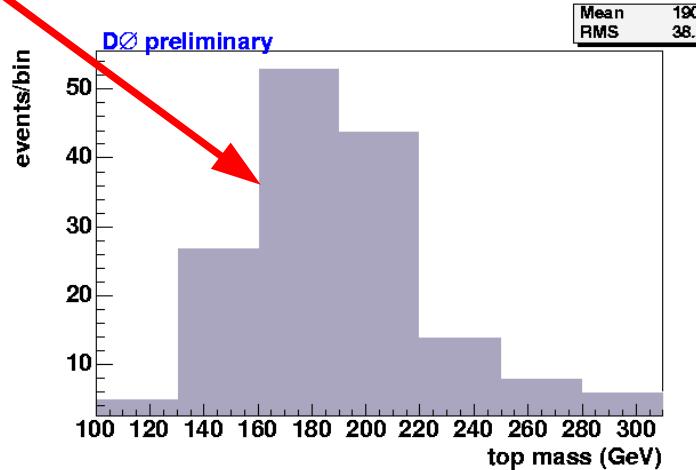
- Identify two leptons
- Scan over top mass
- Solve for top momentum
- Assign weight to solution
- Choose most likely m_t for each event
- Perform binned maximum likelihood fit to **signal** and **background** templates

$$\text{PDF's} \\ w = f(x) f(\bar{x}) \times p(E_l|m_t) p(E_{\bar{l}}|m_t)$$

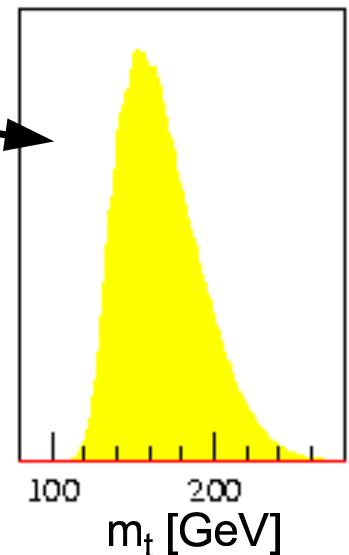
lepton consistency
with m_t



$m_t = 175$ GeV signal template



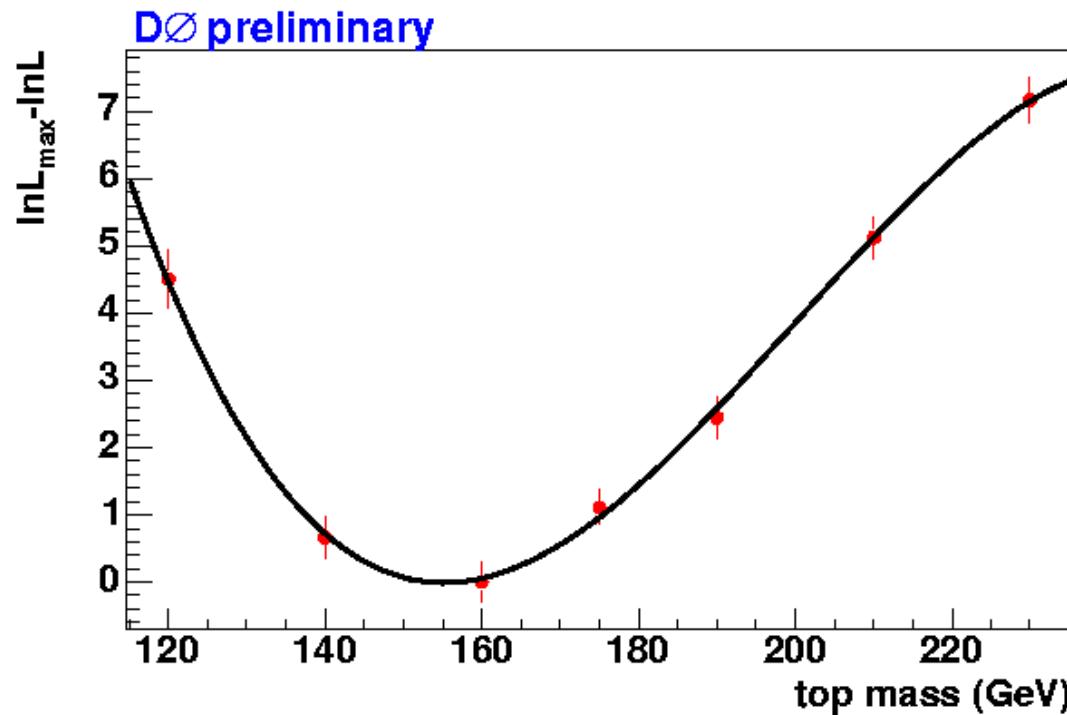
$WW \rightarrow e\mu$ background template



Matrix Weighting Method Results



230 pb⁻¹ data sample, 13 events selected,
2 events expected background



$$m_{top} = 155^{+14}_{-13} (stat) \pm 7 (syst) \text{ GeV}/c^2$$

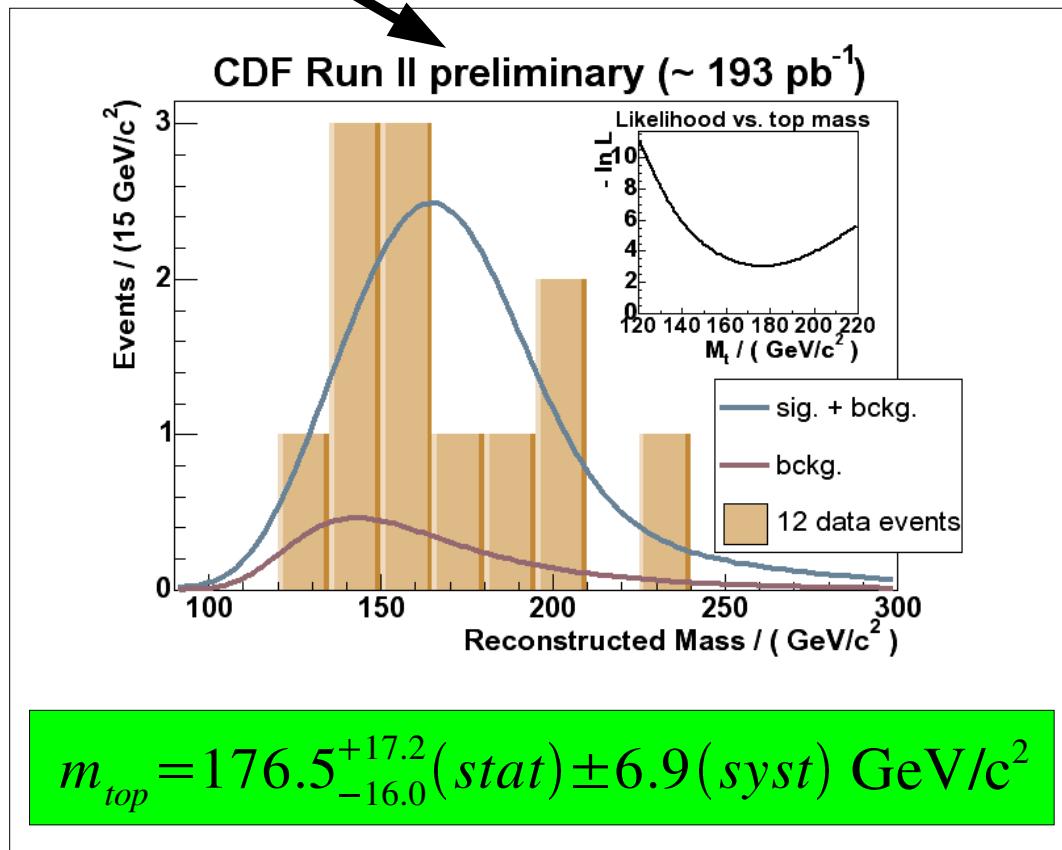
ϕ weighting and P_z weighting



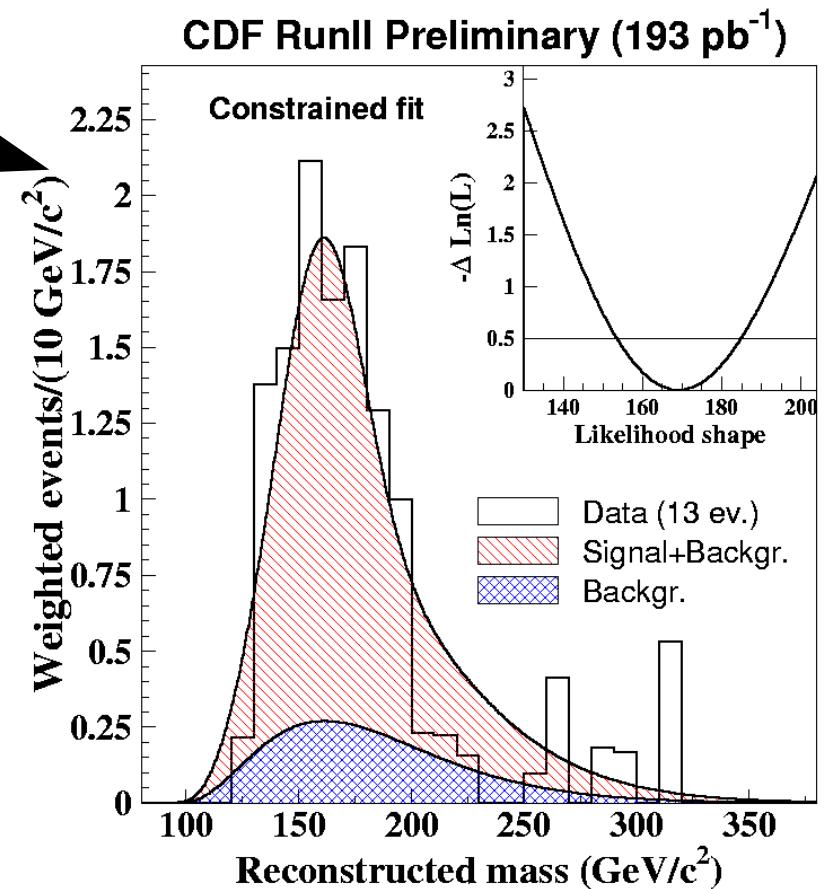
Two approaches:

- Scan over neutrino ϕ 's, use weight distribution
- Scan over p_z of $t\bar{t}$ system, select most likely m_{top}

$$m_{top} = 170.0 \pm 16.6(stat) \pm 7.4(syst) \text{ GeV}/c^2$$



$$m_{top} = 176.5^{+17.2}_{-16.0}(stat) \pm 6.9(syst) \text{ GeV}/c^2$$



193 pb^{-1} data sample
12-13 events selected
2.7 expected background events

Neutrino Weighting Algorithm



Weight according to
neutrino pseudorapidity

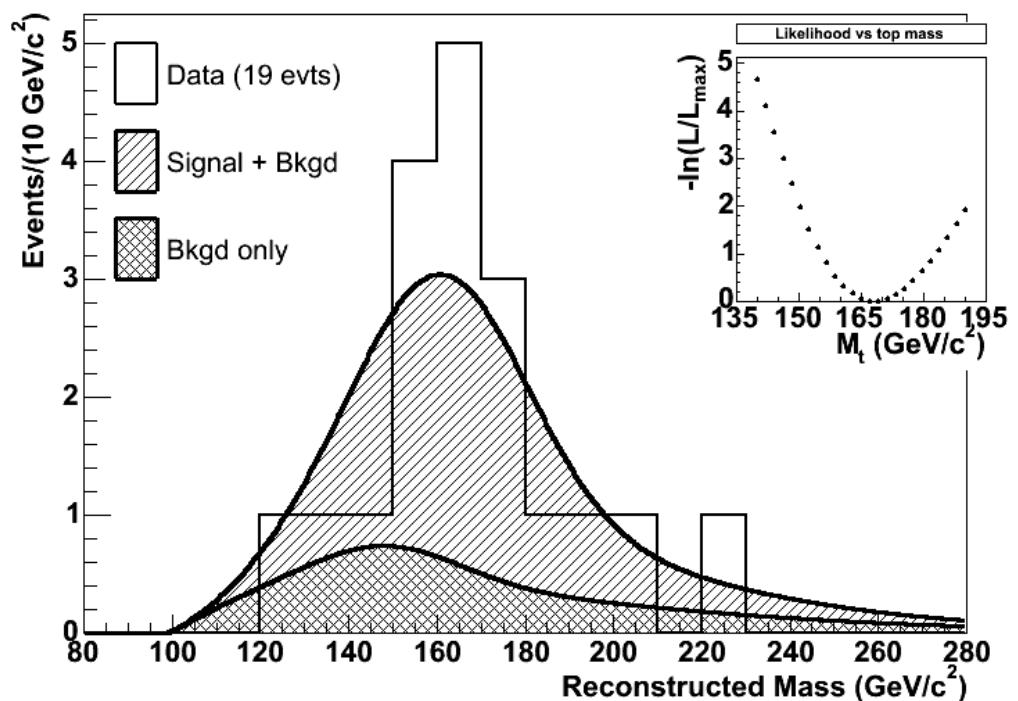
197 pb⁻¹ data sample, 19 events selected
6.6 events expected background

Looser selection requirements:

- Select one electron or muon
- Select isolated track

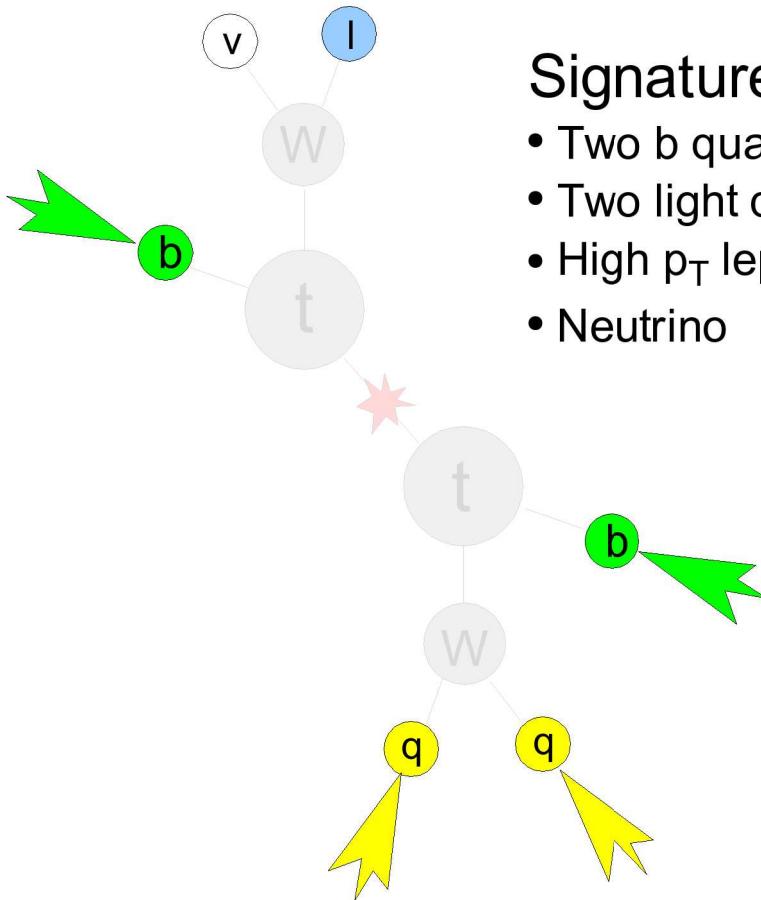
Systematic Uncertainties

JES	7.4
Background shape	2.8
Signal temp. stat.	0.3
Bkgd. temp. stat.	1.3
MC generators	0.6
PDFs	0.8
ISR	2.5
FSR	1.3
Missing E _T Resolution	0.3



$$m_{top} = 168.1^{+11.0}_{-9.8} (stat) \pm 8.6 (syst) \text{ GeV}/c^2$$

Lepton+jets channel



Signature:

- Two b quarks
- Two light quarks
- High p_T lepton
- Neutrino

Typical Event Selection:

- One high p_T lepton (>20 GeV)
- Four or more high p_T jets ($>15/20$ GeV)
- Missing E_T (>20 GeV)
- b-tagging (optional)

Backgrounds:

- W+jets
- Multi-jet with fake lepton

Larger branching ratio → better statistics

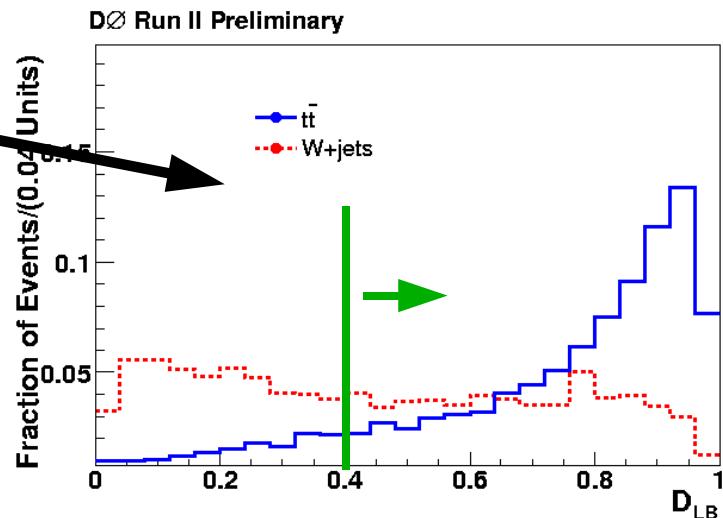
More background

One neutrino → overconstrained kinematics

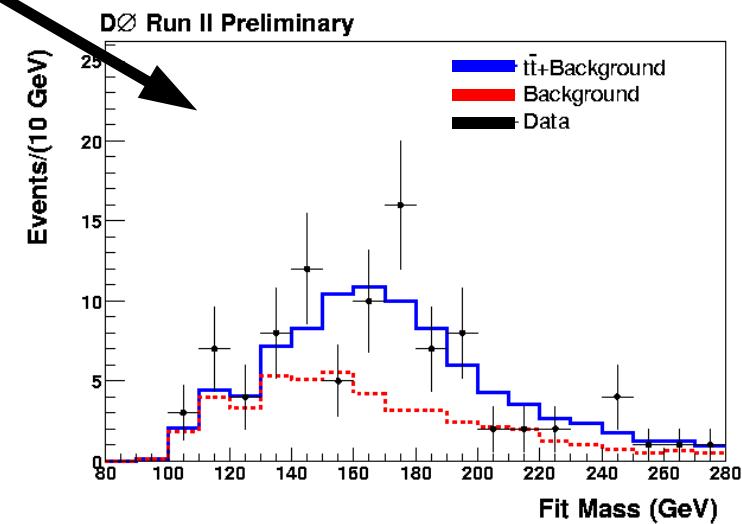
Template Method



- Low bias discriminant ($D > 0.4$)
 - Aplanarity, etc.
 - Improve S/B, weakly correlated with m_{top}
- Kinematic fit
 - Keep lowest χ^2 solution ($\chi^2 < 10$)
- Fit with signal, background templates



4 jets →
12 unique jet solutions
(x 2 neutrino p_z choices
= 24 unique solutions)



230 pb⁻¹ data sample, 94 events selected

$$m_{top} = 169.9 \pm 5.8(stat)^{+7.8}_{-7.1}(syst) \text{ GeV}/c^2$$

Template Method With b-Tag



- No cut on discriminant
- Looser jet p_t cut ($20 \rightarrow 15$ GeV)
- Require at least one secondary vertex tag

Topological purity: 51%
b-tag purity: 76%

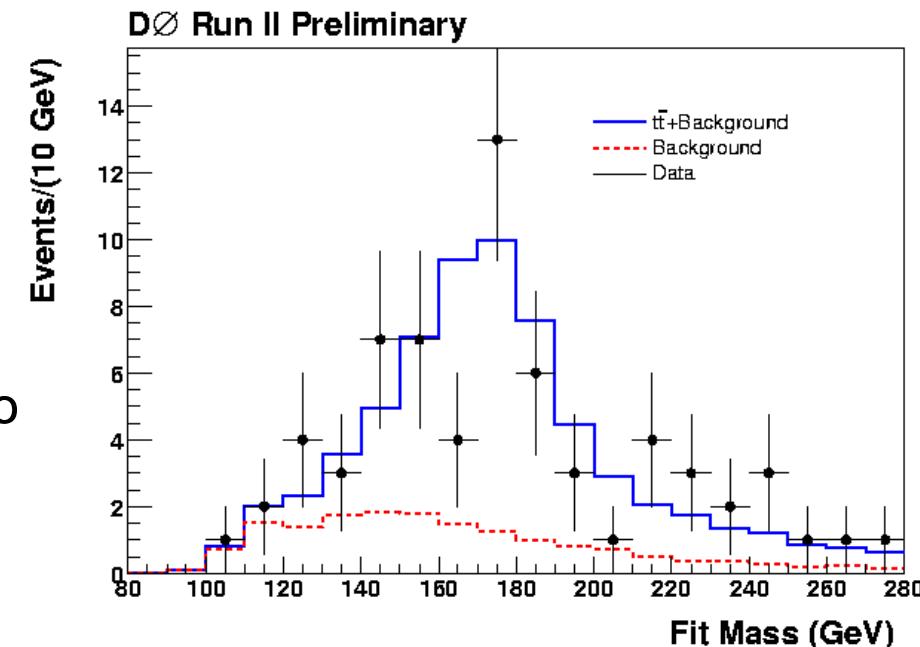
b-tag also reduces combinatorics

Systematic uncertainties

Jet energy scale	5.0
Jet Resolution	0.9
Gluon Radiation	2.4
Signal Model	2.3
Bkgd Model	0.8
b-tagging	0.7
Calibration	0.5
Trigger Bias	0.5
MC Statistics	0.5

6.7 in topo analysis

230 pb⁻¹ data sample, 69 events selected



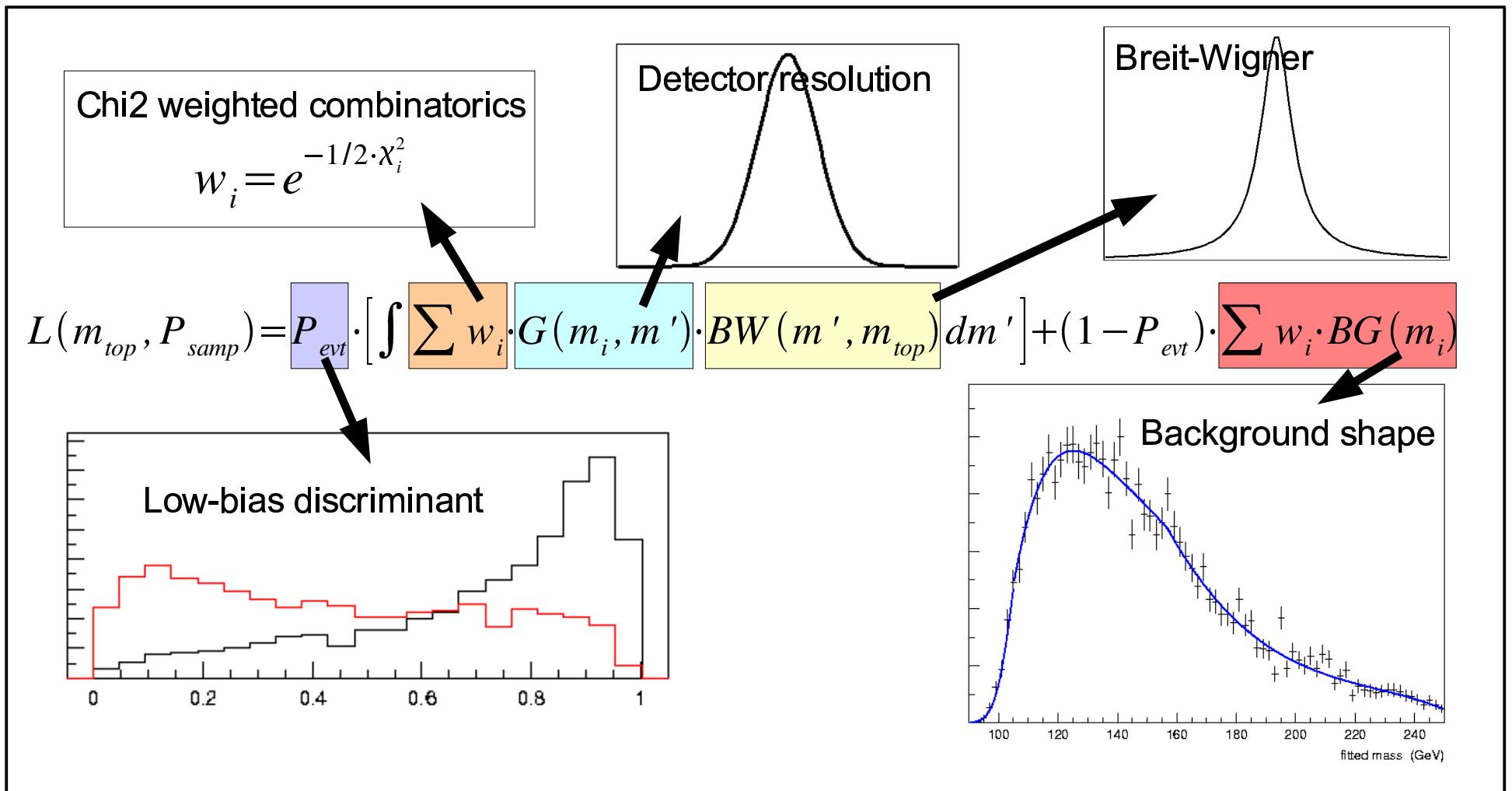
$$m_{top} = 170.6 \pm 4.2(stat) \pm 6.0(syst) \text{ GeV}/c^2$$

reduced systematic uncertainty

Ideogram Method



- Uses same kinematic fit as Template Method
- Includes low-bias discriminant in likelihood fit
- Calculate likelihood for each event in sample



Ideogram Results

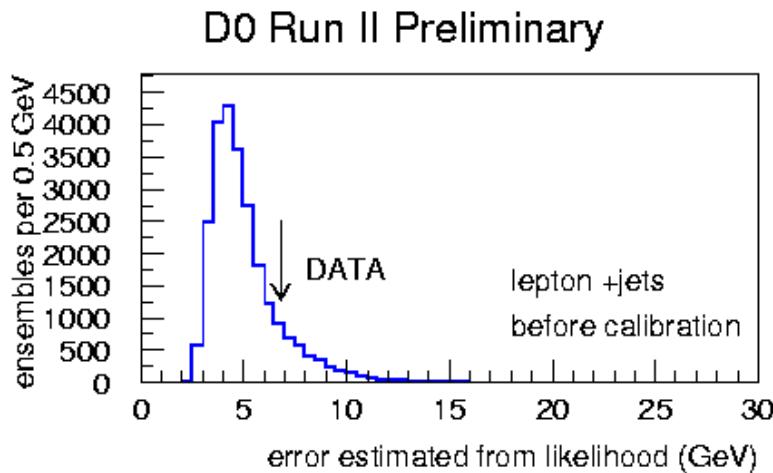


Increased statistical sensitivity:

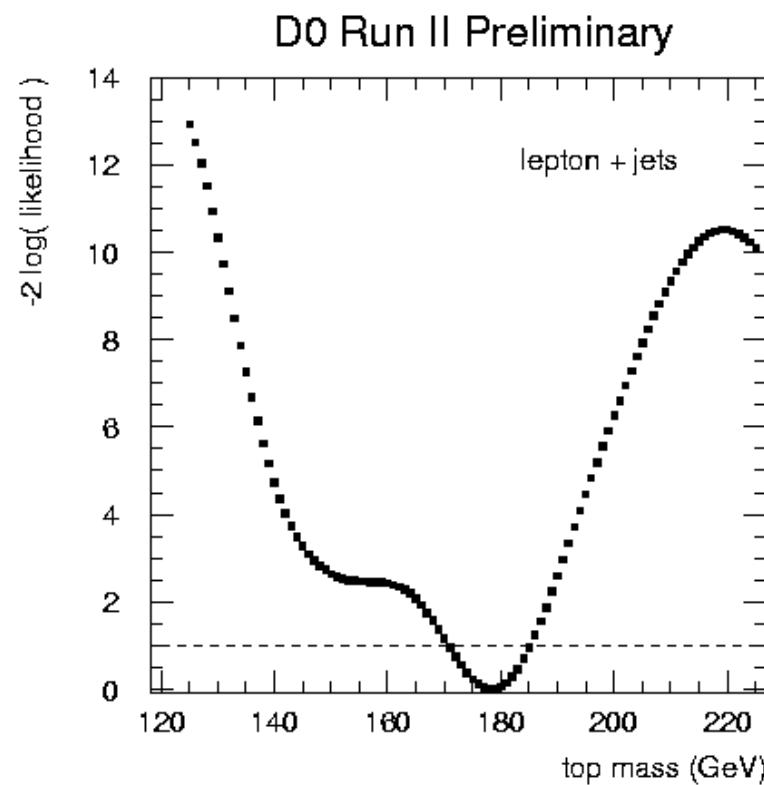
Expected statistical uncertainty
with 160 pb^{-1} data sample

- Template Method: 6.3 GeV
- Ideogram Method: 4.6 GeV

Expected statistical uncertainty
for Ideogram Method



160 pb^{-1} data sample, 191 events selected



$$m_{top} = 177.5 \pm 5.8(\text{stat}) \pm 7.1(\text{syst}) \text{ GeV}/c^2$$

Dynamic Likelihood Method



Selection requirements:

- Exactly four jets ($E_T > 15$ GeV)
- One or more secondary vertex b-tags

Similar to DØ Run I
Matrix Element Method

Calculate event likelihood using
leading order matrix element:

LO Matrix Element

$$L(m_{top}) = \sum \int f(z_a) f(z_b) \cdot f(p_T) |M|^2 \frac{1}{\Phi} w(x|y) dx$$

PDF's

Sum over combinations
(reduced by b-tag)

Initial state p_T

Phase space factors

Transfer function

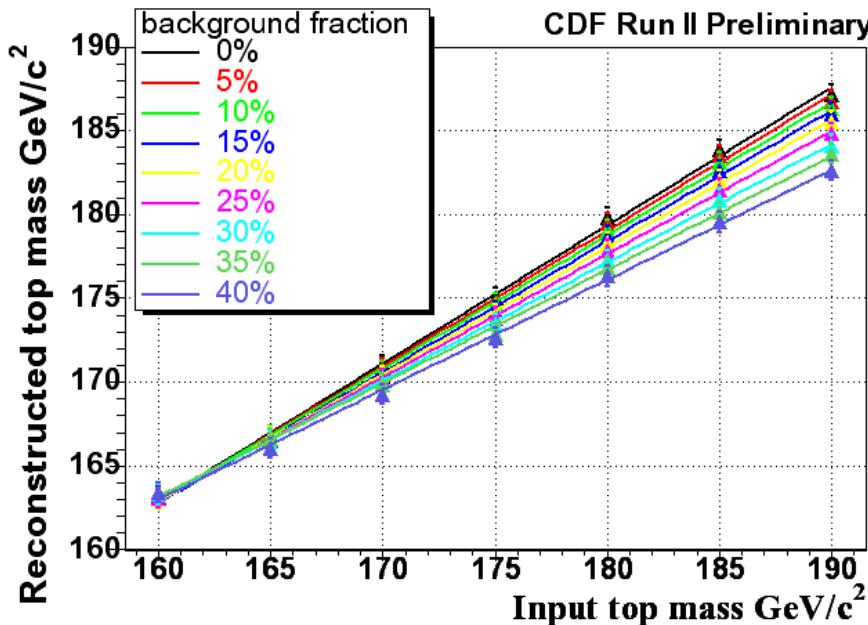
Transfer function parameterizes detector resolution
for both light quarks and b quarks

Dynamic Likelihood Method Results



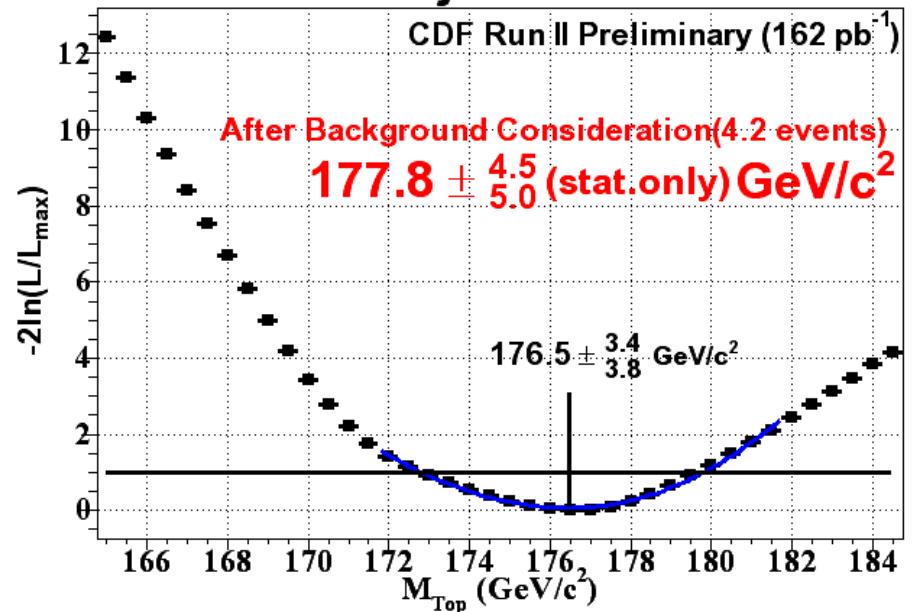
b-tag significantly reduces background

- No background probability term
- Calibrate for m_{top} -dependent transfer function, background



162 pb⁻¹ data sample, 22 events selected
4.2 events expected background

22 events joint likelihood



$$m_{top} = 177.8^{+4.5}_{-5.0} (\text{stat}) \pm 6.2 (\text{syst}) \text{ GeV}/c^2$$

Template Method



Separate analyses for tagged,
untagged samples

b-tagged sample:

- 3 jets with $E_T > 15$ GeV
- 4th jet with $E_T > 8$ GeV

untagged sample:

- 4 jets with $E_T > 21$ GeV

signal/background
in 2-tag sample: 18/1

Continuous templates:

$$f(m_t | M_{top}) = A \cdot G(m_t) + B \cdot T(m_t)$$

parameters of f vary with M_{top} :

$$p_i = a_i + M_{top} \times b_i$$

Unbinned Likelihood Fit:

fit to the data

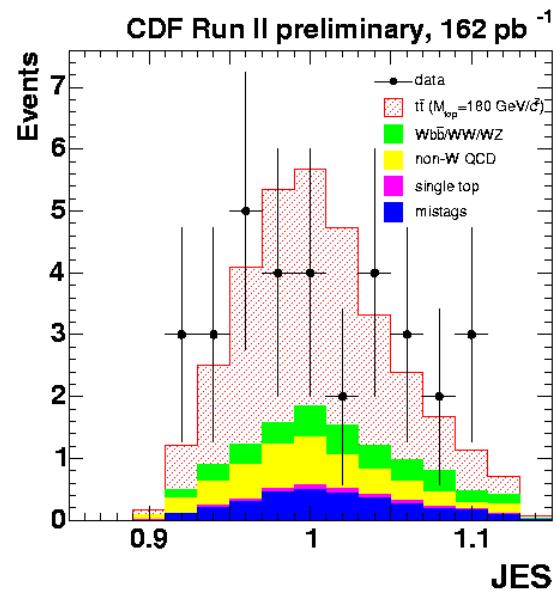
$$L(m_{top}) = L_{shape} \times L_{signal}$$

signal fraction constraint

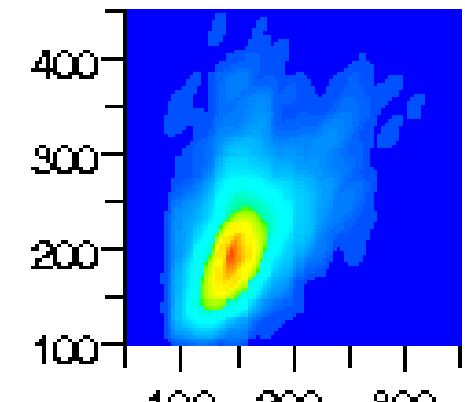
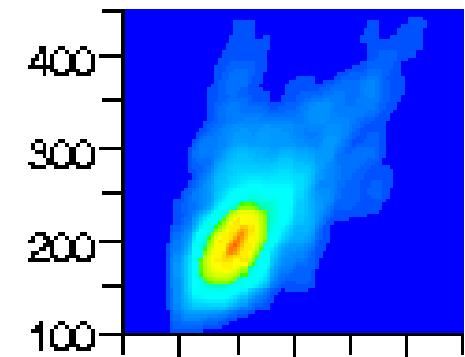
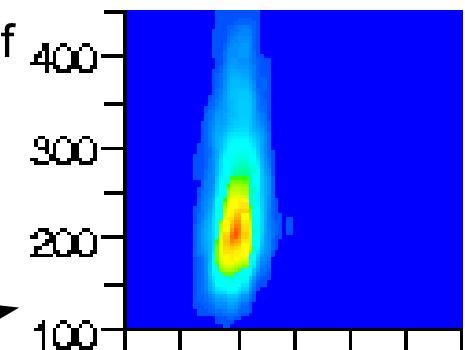
Multivariate Template Method



- 2-D template fit of m_{top} and scalar sum of four jet E_T
- At least one b-tag
- Jet energy scale varied event-by-event
- Templates for three event categories
 - Correct jet permutation
 - Incorrect jet permutation
 - Jet not from top decay



scalar sum of
four jet E_T



JES constraint
parameter can be
tuned to optimize
total uncertainty

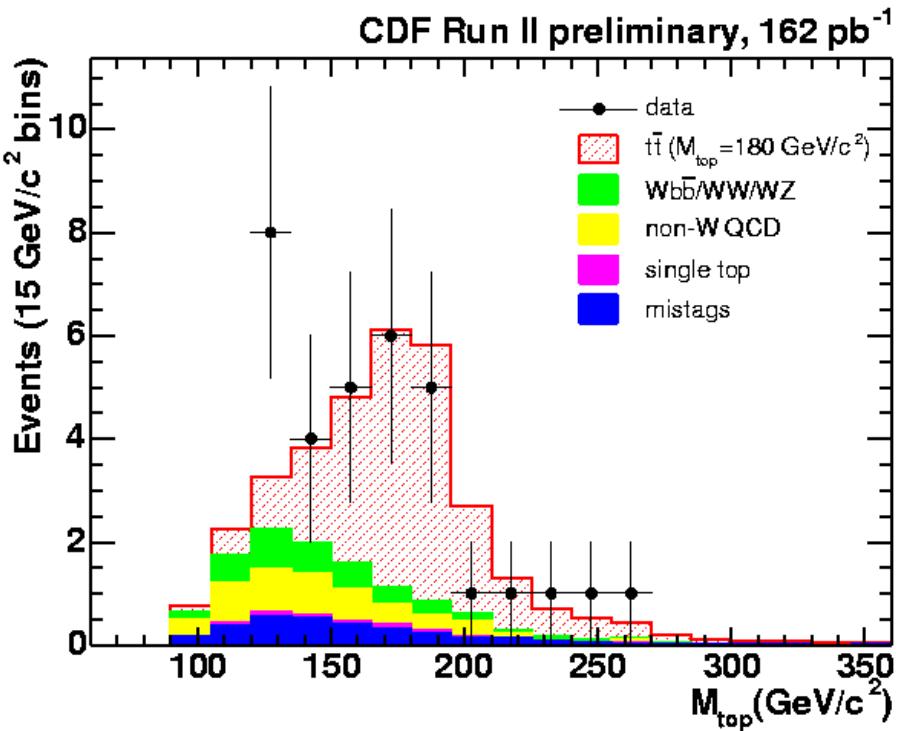
Reconstructed Mass
(150 GeV MC sample)

Template Method Results



Multivariate Template Method

162 pb⁻¹ data sample, 33 events selected



$$m_{top} = 179.6^{+6.4}_{-6.3} (\text{stat}) \pm 6.8 (\text{syst}) \text{ GeV}/c^2$$

Template Method

318 pb⁻¹ data sample,
138 events selected



Two approaches:

- “Standard” template method

$$m_{top} = 173.2^{+2.9}_{-2.8} (\text{stat}) \pm 3.4 (\text{syst}) \text{ GeV}/c^2$$

- Template method with in-situ
 $W \rightarrow jj$ JES determination

$$m_{top} = 173.5^{+2.7}_{-2.6} (\text{stat}) \pm 2.5 (\text{JES}) \pm 1.7 (\text{syst})$$

Total uncertainty = 4.1 GeV
Better than Run I world average

Jet Energy Scale

Top mass measurements require knowledge of parton energy \rightarrow Jet Energy Scale

$$E_{\text{corr}} = \frac{E_{\text{meas}} - O}{R \times S}$$

Response Correction:
Hadronic response
Uninstrumented regions

Offset Correction:
Multiple interactions
Underlying event

Showering Correction:
Particles outside of cone

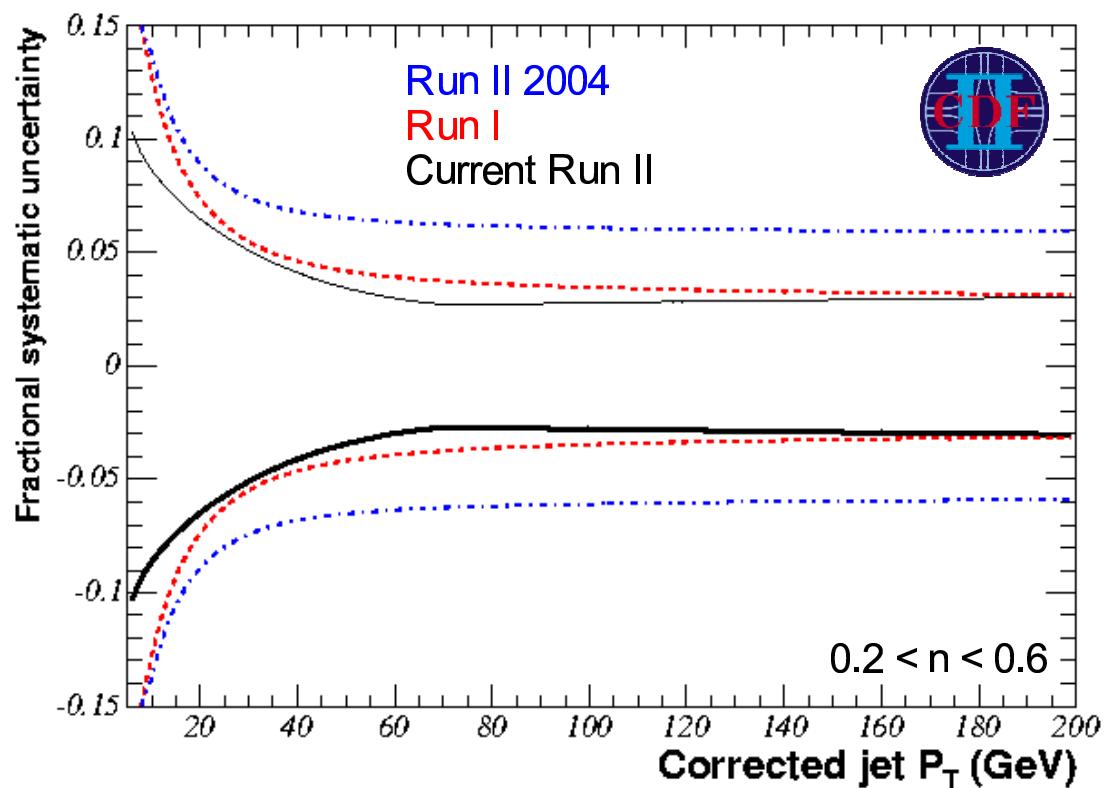
Different components of JES derived from:
Zero bias and minimum bias events
Photon + jet events
Z + jet events
Dijet events
Both data and Monte Carlo

Jet Energy Scale

JES uncertainty is the dominant systematic uncertainty for all top mass measurements, and of the same size as statistical error for lepton+jets

Significant improvements
in JES uncertainty

Approaching point where
JES scale set by W mass
in top measurements



Other Systematic Uncertainties

Some systematic uncertainties will decrease with more integrated luminosity

- Part of JES
- Jet resolution
- Trigger
- Background fractions

CDF DLM	
Jet energy scale	5.3
Transfer function	2.0
ISR	0.5
FSR	0.5
PDF	2.0
Generator	0.6
Spin correlation	0.4
NLO effects	0.4
Bkgd fraction	0.5
Bkgd modeling	0.5
MC Modeling	0.5

Other systematics will not scale with integrated luminosity

- Part of JES
- Initial and final state radiation
- Signal and background modeling
- PDFs

DØ b-tag Template	
Jet energy scale	5.0
Jet Resolution	0.9
Gluon Radiation	2.4
Signal Model	2.3
Bkgd Model	0.8
b-tagging	0.7
Calibration	0.5
Trigger Bias	0.5
MC Statistics	0.5

Top mass becoming systematics dominated

Summary

- Tevatron Run II is producing excellent top results
- Diverse collection of sophisticated analysis methods
- New round of results with $>300 \text{ pb}^{-1}$ beginning to arrive
- Will eventually have 10x current data sample
- In ten years, top quark has gone from discovery to precision

